# Performance of the Wireless Ad hoc Network W-CHAMB

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*Abstract* — **A wireless ad hoc multihop network for packet and channel switched communication is introduced and protocols for the air interface are described and evaluated. Ad hoc networks can be realized owing to the ability of stations to route connections according to the current meshing of the network. The decentrally organized network is able to guarantee the bandwidth contracted to a connection in a hidden station environment by means of contention-free data transmission for both, channel and packet switched services, based on real channel connections (RCCs). Channels are established and used for the duration when packets wait for transmission in queues, released when no more packets are to be transmitted, and are re-established when the next packet arrives. Most efficiently use of the spectrum capacity is provided by a mechanism for dynamic channel allocation to services. To guarantee available capacity of the network for the re-establishment of a connection, connection admission control is applied considering the overall interference situation and the current meshing.**

**A performance evaluation of the proposed protocols is given by means of a simulation study in example scenarios.**

## I. Introduction

Currently available systems that support ad hoc communication for data rates up to 2 Mbit/s at the frequency band of 2.4 GHz are the standard IEEE 802.11 [1], [2], and at 5.2 GHz with a max. data rate of 23.5 Mbit/s HIPERLAN[1]/1 [3], [4]. These systems rely on the MAC[2] protocols carrier sense multiple access (CSMA) with collision avoidance (CA) and EY-NPMA[3], respectively, to assign transmission capacity on a packet basis to competing stations within a radio cell. The probabilistic nature of CSMA/CA is known to be unable to support real-time oriented traffic. Furthermore, these systems suffer from large protocol overhead especially for short data packets, low bandwidth efficiency and no guarantee of quality of service (QoS).

Different from the systems mentioned above the proposed network relies on dynamic channel allocation (DCA) and the concept of real channel connections (RCCs) [5]. No central control is used but all stations decentrally acquire transmit capacity when needed and release it by simply not using it. For point-to-point communication between stations and nodes and between nodes, RCCs are established, used and released, e.g. like in the DECT or PHS systems [6], [7]. An RCC provides capacity for collision-free transmission of packets, e.g. ATM cells, in slots of a framed TDMA system in a hidden station environment. To open a connection (RCC) by a station to the next station, the most silent channel is used. Therefore, each station maintains a local channel occupancy list of the total system's TDM-channels in terms of the received signal strength indicator (RSSI) measured at the station. After opening the connection, all other stations in the receive range of the two stations involved will recognize and respect the occupancy of the channel as long as they measure a defined level of signal strength.

RCC based systems are potentially better suited to guarantee an agreed transmission capacity in an ad hoc environment than systems based on dynamic slot assignment [8], [9], [10], [11], [12], or random MAC protocols, due to the unpredictability of the random usage of the radio medium in the receive range of any station involved. Consequently, in Section IV a concept for the wireless air interface is introduced that relies on the use of RCCs. The system is able to guarantee a negotiated QoS based on a spectrum-efficient connection admission control (CAC) that is introduced in Section IV.G. Performance results of the ad-hoc multihop radio network demonstrating its ability to guarantee the QoS are presented in Section VII.

## II. Multihop Operation and Hidden Stations

Self organization is a requirement for ad hoc radio networks. Since the terminals are operated independently in a given area, radio coverage planning is impossible to apply.

In many cases not all of the terminals will have a direct radio contact to each other. Instead a partial connectivity (see also Section VI) will result and will require a radio relay function implemented in stations to support a multihop operation (with typically a small amount of hops only). Multihop packet radio networks have been studied extensively [13] and have been found to be extremely difficult to organize so as to make efficient use of the spectrum capacity assigned. These systems suffer from hidden stations. A station, forwarding a packet to some other station is unable to control the usage of the respective time slot in the receive range of the station addressed.

Fig. 1 depicts the situation where node N1 has a detection range $R_{dt}$ which is larger than its transmit range $R_{tx}$ and smaller than its interference range $R_I$, allowing node N1 to listen before talking so as to avoid a collision of its packet transmitted to station $S1$ with other packets transmitted from stations in the detection range $R_{dt}$ of node N1. The potential collisions for the nodes N1 and N2 as well as stations S1 and S2 are displayed. Since $S3$ and N2 are hidden stations to N1 with respect to a transmission of N1 to $S1$ these stations behave like transmitters applying the pure ALOHA access protocol, and collisions will occur when N1 transmits to $S1$ even when the channel was sensed before.

Another problem in partially meshed networks that decreases the spectral efficiency are exposed stations [14]. A station is called exposed if it resigns to transmit at some time to not interfere another communication relationship but in fact could communicate without disturbing the respective communication.

[1] HIPERLAN: High Performance Radio Local Area Networks
[2] MAC: Medium Access Control
[3] EY-NPMA: Elimination Yield-Non-Preemptive medium access control, used in HIPERLAN/1

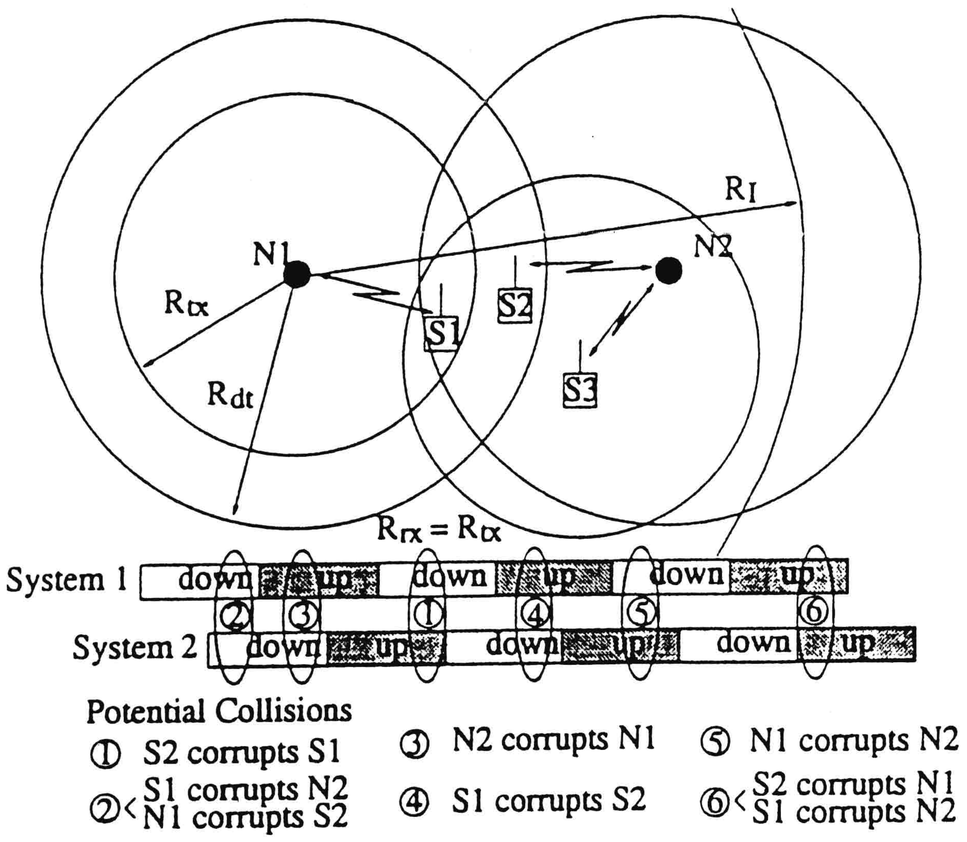


Fig. 1: Interferences for non-synchronized systems in a hidden station environment

Exposed and hidden stations affect the system throughput severely and hidden stations tend to make a QoS guarantee for ATM virtual channel connections (VCCs) impossible. The problem always arises when no means are available in a system to extrapolate from the presently observed spectrum occupancy to the future usage, e.g. of a time slot. The use of the real channel connection (RCC) has the advantage that an RCC measured by some station to have a too high signal strength will not be used by that station, since with high probability it will find the channel still occupied in the near future.

A multihop network is able to serve different applications. One is the connection of fixed, movable or mobile stations to a fixed network access point across a so-called ad hoc network, in which stations themselves identify their current radio connectivity at their current location with the other active stations and calculate the route across intermediate (relay) stations to the final destination station [15]. Typical applications for this include the replacement of an indoor local area network (LAN) by a wireless LAN, say at 5.2 GHz. Another application is a radio LAN outdoors.

In the following a wireless ad hoc multihop network is presented that is optimized for the applications described above.

## III. W-CHAMB Architecture

Different from HIPERLAN/2 [12] there is no central control node but only stations in the Wireless Channel-oriented Ad hoc Multihop Broadband (W-CHAMB) network, able to route forward packets received according to VCC established beforehand [16]. Stations with reduced complexity that have no routing functionality can also participate in the network. Those stations reduce the connectivity but behave like other stations.

One version of the network is a radio access system providing standard ATM-Forum UNI/NNI interfaces at the terminal and network sides, respectively. Terminal adaptors (TA) contain the functions of radio modems and are used to bridge the wireless medium by means of the radio physical layer (RPL), medium access control (MAC) and logical link control (LLC) layers. Of course, also wireless IP packets can be served by the network, and the respective interface to the IP convergence layer is foreseen in the W-CHAMB protocol stack [17].

## IV. Protocols of the W-CHAMB

### A. Establishment of an End-to-end VCC

Before the data transmission starts, an end-to-end VCC with a new VCC-ID is established. To transmit the VCC set-up request to the next station on the end-to-end connection exclusive transmit capacity on the MAC layer for the point-to-point communication is reserved by means of an RCC. The notion of an RCC is used to define the transmit capacity assigned to a link between two communicating stations in terms of one ore more traffic channels (TCHs). TCHs are using frequency/time division multiplexing (FDM/TDM) channels of the physical layer. A TCH x/y is using a number x of slots per frame, where y is the repetition period of these slots counted in frames [14].

The destination station during VCC set-up can be retrieved from a station's local routing table that contains the one-hop next station for an end-to-end connection. If the RCC has been established, a connect request signaling PDU is transmitted to the one-hop (next) station that comprises the address of the end-to-end destination station. In case the addresses of the one-hop station and the end-to-end station are different, the station stores the new VCC-ID and the quality of service parameters and relays the connect request to the next station on the multihop connection. The destination station will respond with a connect confirm PDU that will be relayed by the intermediate station(s) to the source station and the new VCC is established then.

To protect the existing VCCs and to avoid the situation that the network will be overloaded, each station involved in the set-up procedure performs connection admission control, as explained in Section IV.G, and rejects the connection request if sufficient capacity is not available.

### B. Operation of RCCs

*1) Set-up of an RCC* Transmit capacity as long as needed is provided by RCCs [14]. An RCC is set-up when a PDU has to be transmitted to the next station and no RCC between the stations involved exists. To establish an RCC between two stations an access (ACC) protocol data unit (PDU) is transmitted via the access channel (ACH) as described in [16]. The PDU contains an ID to identify the type of PDU, e.g. access control or network management, and the addresses of the transmitting and receiving stations of the one-hop connection. An abbreviated unique VCC identifier (VCC ID) refers to a VCC that has been previously established (if the network does support QoS guarantees), and a channel list contains the proposed channels that have been measured to be silent and can be used by the responding station to acknowledge the requested RCC. The destination station if reached selects one out of the proposed channels according to a minimum required RSSI margin value out of its local channel occupancy list and responds to the calling station in the respective TCH with an acknowledge PDU (ACK PDU) in the same frame.

*2) Data Transfer on an RCC* After an RCC has been established, the data transfer is started. The packets are transmitted transparently as payload of the data PDU in a time division duplexing (TDD) mode of operation and are acknowledged on the backward channel per PDU or once per $i$ ($i > 1$) PDUs.

*3) Connection Release of an RCC* If no more PDUs have to be transmitted on the respective RCC, it is released to provide this capacity to other one-hop connections for data transmission. An RCC is released either explicitly through a connect release message from one of the stations involved in a hop, or by a decentralized decision from the other stations observing that a pre-defined time the respective slots in the frame have not been used.

### C. Power Saving

Power saving is important in wireless LAN with movable or mobile stations due to their limited battery capacity. The proposed scheme is able to support some percentage of mobile stations unable to continuously follow what is going on and possibly being not willing to relay traffic of other stations. The latter has no impact on the functioning of the network but only on the meshing density, since the connectivity of stations is reduced then. Stations that are not willing to transmit may switch to a sleeping mode. To enable stations to be addressed and reached even when sleeping, sometimes they must select a nearby (fixed) station and inform it when during their next planning horizon they will power on and be ready to receive.

### D. Network Management

During connection setup of a virtual end-to-end connection management related data, e.g. routing information will be transmitted. At the same time the routing tables are updated in all stations that become aware of the VCC and the VCI/VPI tables and respective VCC identifiers for the sequential one-hop connections are assigned. To update the routing tables, centralized and distributed algorithms can be used [18]. The shortest path algorithm (min-hop algorithm) is used to find the destination station on a multihop connection. Other routing strategies that can be applied during VCC connection setup and for routing updates due to topology changes have been published in [19], [20], or [21]. The radio connectivity can be retrieved from local channel occupancy list in the stations that is supervised by the station's management system by measuring the RSSI of the periodic slots during each frame, and that is updated during connection setup of RCCs. An organization channel is used to exchange system connectivity information, parameters of the stations and network management system and radio resource related information. Additional routing table updates will be performed periodically on the organization channel, too.

### E. Organization Channel

The organization channel (OCH) can operate under central or decentral control. In the W-CHAMB a TCH x/y will be used for the OCH throughout the network as explained in [16]. Depending on the number of slots per frame the parameters x and y are chosen to provide the required capacity for the updates.

### F. Handover

The simplest way to perform a handover is to reastablish the VCC if some hop is not available anymore. More sophisticated procedures have been introduced, e.g. virtual tree [22]. In the W-CHAMB each station has switching capabilities allowing to reroute a VCC. This message exchange needed to accomplish fast handover involves receiving a message at the old station and sending it to the new station as described in [23].

### G. Connection Admission Control

To be able to support real-time services with an appropriate QoS, these services are assumed to open a virtual channels connection before transmitting user data as described in Section IV.A. A decentralized connection admission control (CAC) algorithm has been developed that is able to guarantee the QoS aimed at. Non real-time services need not to apply for admission but will be interrupted whenever real-time services need the radio capacity occupied by them. Of cause it appears practical also to apply some admission rules for non real-time services to guarantee them at least some minimum average throughput. CAC is used to prove whether a new connection can be established resp. the service parameters are allowed to change, or whether the request has to be rejected to protect other existent connections and to guarantee the negotiated QoS. Since most of the data sources are characterized by a variable bit rate, the task of the CAC is to estimate the equivalent bit rate of the data source based on the traffic characteristics of the potential new connection and the traffic characteristics for the currently connected sources.

Algorithms known from fixed networks can be used to estimate the equivalent capacity (equivalent bit rate) of a VCC in W-CHAMB, cf. [24]. If enough physical channel capacity is avaliable to transmit the equivalent bit rate, the packet loss probability will be less than $P_{loss}$. Packets can be lost due to buffer overflow or expiration of the life time in case of real-time traffic. Since the CAC relies on the available capacity, it has to be estimated in wireless systems. The radio capacity seen by a station depends on the number of repeated transmission per hop and the number of non-interfered channels. To assess the available capacity for a new virtual connection the equivalent capacities of all stations within the detection radius of the considered station and parameters of the new VCC are taken into account and make up the equivalent capacity $C_{new}$. Since $C_{new}$ is below the total capacity $C_{total}$, the new connection is accepted. A new virtual end-to-end connection will be accepted if on every link this procedure is successful.

A further approach suitable for the proposed network can be found in [25], that reserves capacity based on the peak rate of real-time oriented services and the access delay needed to contend for the respective RCCs. It is also described there how prioritized services can interrupt other services to be able to meet their transmission requirements.

## V. Traffic Models

The protocols described beforehand have been analyzed with stations that have identical source traffic behaviour and generate symmetric traffic. Two traffic sources are modeled by a Poisson stream of packets with constant length either of 53 byte (source 1) or 1590 byte (source 2) corresponding to a bulk arrival of 30 ATM cells. Both sources intend to model data traffic. A third class (source 3) is modeled by an autoregressive process of first order with constant packet interarrival time of 33 ms [26] and is used to model VBR traffic sources with mean packet sizes between 206 and 1856 byte.

## VI. Connectivity and Channel Re-use

The connectivity of a radio network is defined by the mean number of stations reached in one radio hop (neighbour), normalized by the number of all the other stations $N$,

$$c = \frac{1}{N(N-1)} \sum_{i=1}^{N} n_i, \qquad (1)$$

where $n_i$ is the number of neighbours to station $i$. For a fully meshed network the connectivity is 1, whereas for a partially meshed network with a mean number of 2 hops for an end-to-end connection the connectivity is 0.5.

Channels can be re-used if the C/I is sufficiently high. For any new connection, the current interference situation is considered for the stations involved and only those physical channels are considered as candidates that have at source and sink stations at least $C/I = 15\ dB$. A free-space pathloss model is used here. Physical channels are detected as reserved if the interference power is at least 4 $dB$ above the noise floor. Under these assumption no channel re-use is possible in the networks that have been investigated in Section VII.

## VII. Performance Results

The protocols described above have been analyzed by means of event-driven stochastic simulation. Different radio connectivities of 20 stations distributed uniformly in an area have been considered and the impact on the performance of end-to-end connections have been investigated. Stations once for ever randomly select their final destination station and service class. No signal fading is taken into account; the packet error ratio (for all PDUs) is set to 1 % instead.

For the following simulation study, the maximum allowed time that an RCC is not used until it is released (maximum allowed inter-car gap, see [27]) is assumed to be two frames.

*1) Impact of the Connectivity on Throughput and Delay*
Figure 2 shows the payload throughput over the traffic load for networks with connectivity 1.0, 0.77, 0.57 and 0.5 for source 2.

Due to protocol overhead at the air interface the payload throughput is more limited dependent on the connectivity. With a connectivity of 0.5 the network is saturated for an offered traffic of 50 % of the transmission rate. A mean number of 1.9 hops per end-to-end connection for this connectivity has been observed so that the load is approx. twice

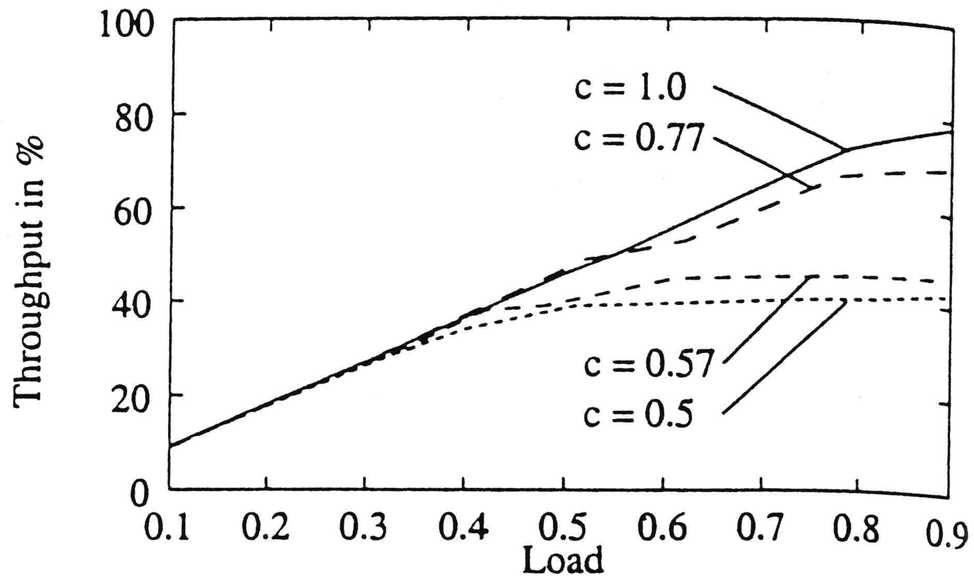


Fig. 2: Throughput vs. offered traffic for source 2

the offered traffic.

Because of the long packets (source 2) and the large sojourn times, trains typically consist of a continuous stream of data PDUs and the one-hop connection is released after each packet. Throughput linearly increases with load until saturation is reached.

For the connectivities of 0.77 and 0.57 the mean numbers of hops per end-to-end connection are approx. 1.3 and 1.5, respectively. It can be recognized that the maximum achievable throughput is very close to this theoretical limit, cf. Fig. 2.

The end-to-end mean delay of ATM cells of source 2 packets shown in Fig. 3 is nearly constant until the network approaches saturation. The capacity of TCHs for each RCC have been increased dynamically with load in this simulation experiment to keep delays small. Under high load the

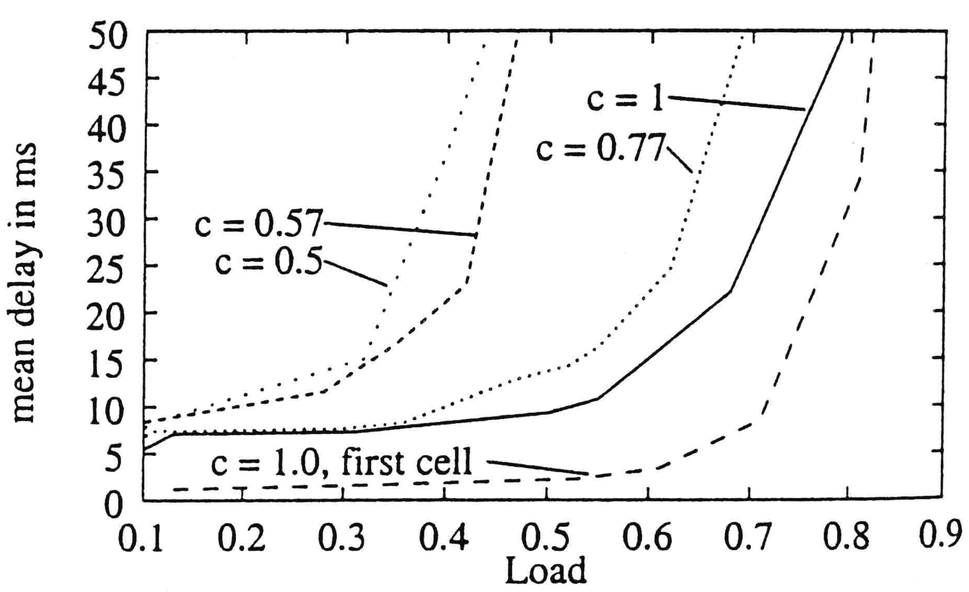


Fig. 3: End-to-end delay vs. offered traffic for source 2

delay increases substantially as the network is then running into high load conditions and queueing in buffers is dominating. The delay is calculated as the mean experienced by a cell of a batch of cells belonging to a packet, cf. Fig. 4. Since some time is needed to increase the number of TCHs

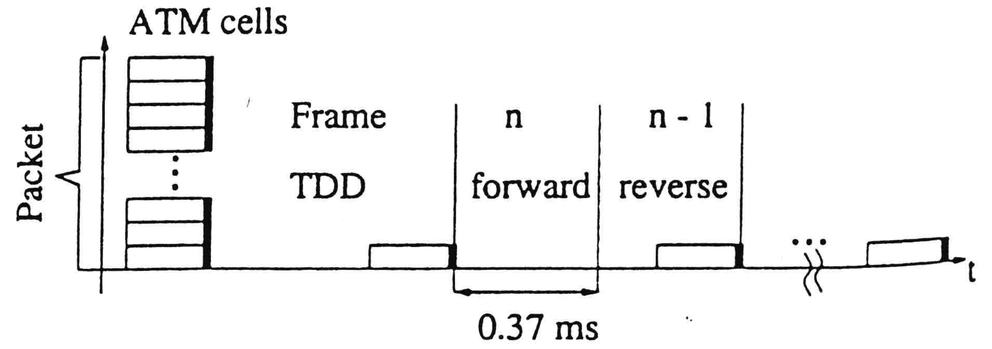


Fig. 4: Batch arrival of ATM cells and the resulting delay

when needed and the max. available transmission rate is

limited to 20 Mbit/s the mean delay per cell increases with the size of the packet. With a TCH 1/1 and a frame duration of 0.37 ms the last ATM cell of a batch of 30 ATM cells will arrive 21.5 ms later than the first cell, resulting in a mean delay of approx. 11 ms if the first cell has a delay of one frame.

As can be seen from Fig. 3 the mean delay of the first cell of a packet is about 1.2 to 3.3 ms up to a load of 60%. The delay of 1.2 ms for low traffic is approx. the mean duration to establish an RCC after a new packet train has arrived. This delay comprises the duration until the next ACH is available, a possible defer phase owing to a collision or unsuccessful contention on the ACH, wait for confirmed reservation of a TCH and the wait for the slot position of the respective TCH.

The delay can be further reduced under small to medium load by allocating traffic channels based on more slots, e.g. TCH x/1, cf. Fig. 5.

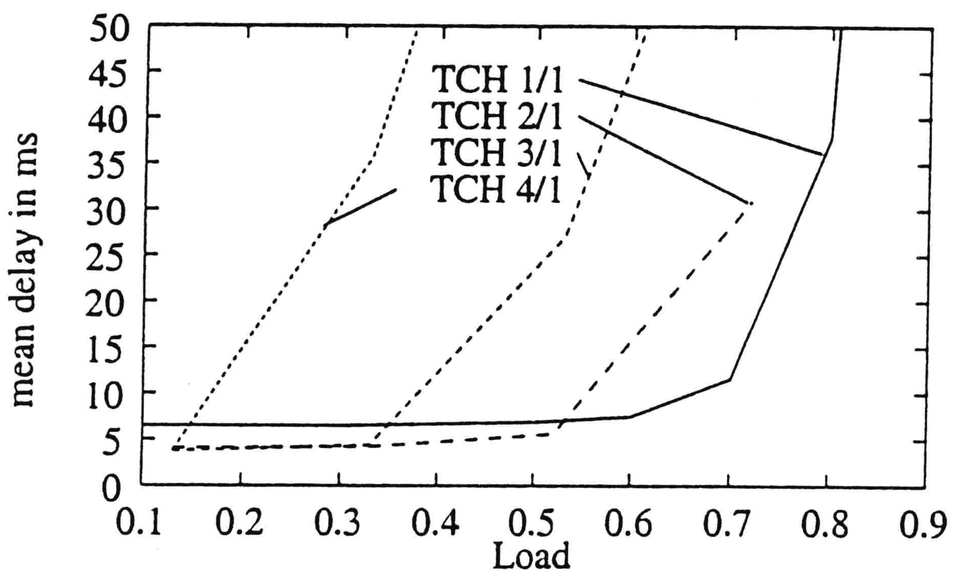


Fig. 5: End-to-end delay vs. offered traffic for source 2, c = 1.0

Using a TCH 4/1 to re-establish an RCC only 4 active RCCs can be supported simultaneously for a frame size of 16 slots. The mean delay for small loads can be reduced since arriving packets are served by a high transmit capacity in a short time. At the same time the blocking probability per hop increases owing to the limited number of RCCs supported in parallel and the system reaches saturation for relatively small loads.

The complementary distribution functions of the ATM cell delay with the load and connectivity as parameters are shown in Fig. 6.

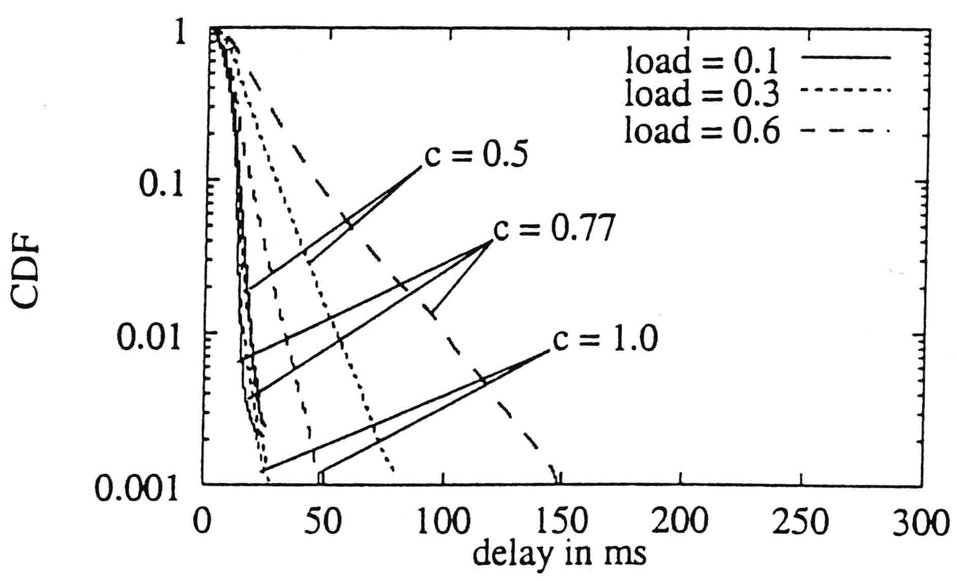


Fig. 6: Delay distribution of the end-to-end delay for source 2

The results for the different connectivities indicate the impact of the multihop connections on the delay and show in detail, how the delay increases with load. For a load of 60 % less than 1 % of the cells exceed a delay of 50 ms for a fully meshed network. It can be recognized that the connectivity has a minor impact on the delay distribution as long as the network is not operating under high load, e.g. the delay distributions for low loads of 0.1 for all connectivities and for a load of 0.3 for connectivities of c=0.77, and c=1 are all very close to each other. Thus, the RCC re-establishment for multihop connections appear to need a very small time amount only and the impact of the transmission time of more than one hop on the delay is relatively small.

*2) Impact of Traffic Sources on the Performance* It has been found, that the throughput is more or less independent of the traffic source characteristics assumed. The mean cell delay with the number of ACHs as parameter is shown in Fig. 7.

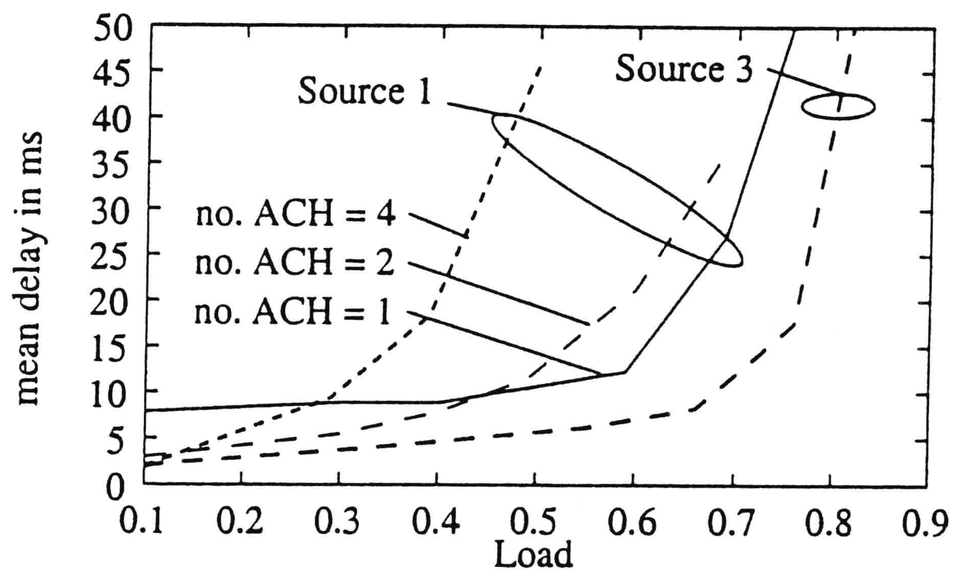


Fig. 7: End-to-end delay vs. offered traffic, c = 1.0

For small traffic load the delay can be reduced by using many ACHs per frame enabling a quick reservation of TCHs especially for short train durations, typical for source 1.

With increasing load the trains tend to become longer and the number of re-establishments of RCCs decreases so that the number of ACHs should be reduced. The mean delay for traffic source 1 applied to all stations is much higher than for VBR traffic (source 3).

Exemplarily, the delay distribution for source 3 is depicted in Fig. 8.

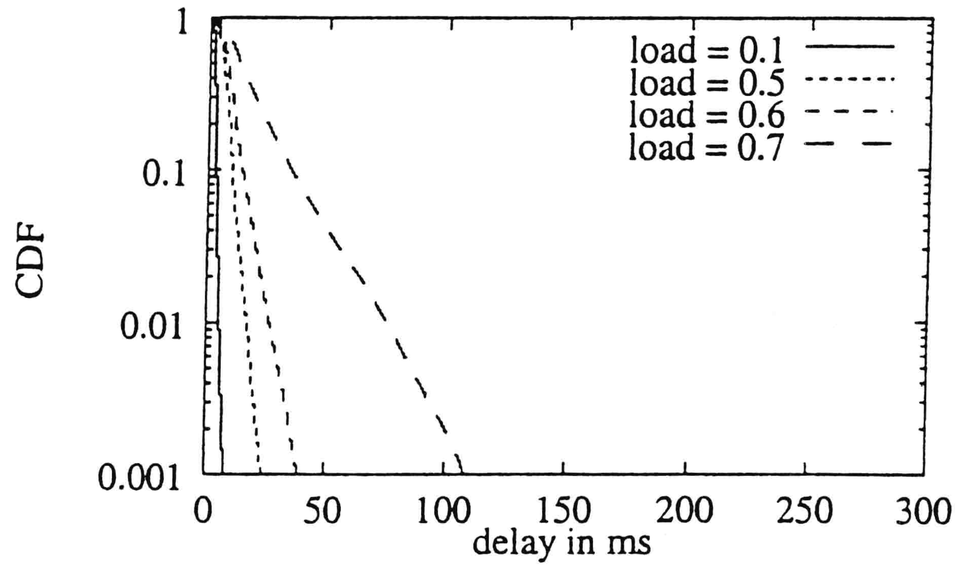


Fig. 8: Delay distribution for source 3, c = 1.0

Under 60% load no ATM cell expires a delay exceeding 45 ms. A W-ATM LAN will typically not be loaded by

rt-VBR services to such a high percentage of its capacity. Since non-real-time VBR and ABR/UBR service classes will be interrupted in favour of rt-VBR if necessary, rt-VBR sources will see a system with a small load only.

## VIII. Conclusion

A self-organized wireless LAN supporting ad hoc and multihop operation with guaranteed QoS has been presented and the performance analyzed. Using real channel connections based on a TDMA frame contention free data transmission can be realized. Even when the network is highly loaded and hidden stations are present a high throughput and a small delay can be achieved with the proposed access control protocol. However, the protocols are unable to reduce the delay below some fixed value (of about 2 ms) needed to establish an RCC connection. The most important features are the fast connection set-up and release to transmit packet trains.

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